A FIVE MW NUCLEAR HEATING REACTOR

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Abstract

The 5 MW Nuclear Heating Reactor (NHR-5) developed and designed by the Institute of Nuclear Energy and Technology (INET) and has been operated for four winter seasons since 1989. During the time of commissioning and operation a number of experiments including self-stability, self-regulation and simulation of ATWS etc. were carried out. Some operating experiences such as water chemistry, radiation protection, and environmental impacts and so on, were also obtained at the same time. All of these demonstrate that the design of NHR-5 is successful.

1. Introduction

The 5MW Nuclear Heating Reactor (NHR-5) developed and designed by Institute of Nuclear Energy Technology (INET) has been put in operation for four winter seasons. The construction of NHR-5 began in March 1986, the civil egineering was completed in september 1987 and the erection of NHR-5 were finished in April 1989. The initial criticality of NHR-5 was reached in Nov. 1989 and full power operation in Dec. of the same year.

In order to expand the utilization of NHR and to improve its economical competition, the operational experiments of cogeneration - heat and electricity and refrigeration for air condition using nuclear steam from NHR-5 were carried out in 1992.

The mile stone of NHR-5 is listed in Table 1.

Table 1 The mile stone of NHR-5

Beginning of construction	Mar. 1986
Completion of civil engineering	Sep. 1987
Completion of erection of reactor	Apr. 1989
Beginning of commissioning	May 7, 1989
Initial fuel loading	Oct. 9, 1989
Initial criticality	Nov 3. 1989
Full power operation	Dec 16. 1989.

The operational practice shows the NHR - 5 has excellent operation and safety features and a high availability of 99%. The parctice also shows the NHR-5 is easy to start up and to be operated. The operation results demonstrated that the NHR-5 has fully reached the design requirements and the main design parameters. Table 2 gives the main operation parameters in comparison with the design values. In the table the operation temperature of the reactor inlet is higher than the design value, which shows the reactor has a larger natural-circulation capability.

Table 2 Main operation parameters of the NHR-5

	Design value	Operation value
Reactor thermal power	5MW	5MW
Reactor		
Outlet temperature	186°C	186°C
Inlet temperature	146.6°C	151°C
Pressure	1.37MPa	1.37MPa
Intermediate circuit		
Primary heat exchanger		
Outlet temperature	142°C	144°C
Inlet temperature	102°C	100°C
Flow rate	107t/hr	97 t/hr
Intermediate heat exchanger		
Outlet temperature	75.2°C	80°C
Inlet temperaure	142°C	144°C
Flow rate	64 t/hr	67 t/hr
Heating grid		
Outlet temperature	90°C	84 °C
Inlet temperaure	60°C	56 °C
Flow rate	143t/hr	152t/hr

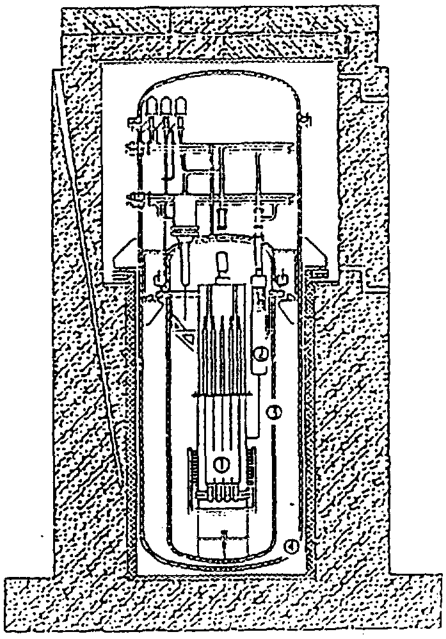
2. Description of NHR-5

The NHR-5 is the first vessel type heating reactor in operation in the world.It is an integrated vessel type light water reactor cooled by natural circulation with self-pressurized performance.

2.1 Structure of NHR-5

Integral and natural circulation

The core and main components of primary circuit are housed within a reactor pressure vessel (RPV). The reactor core is located at the bottom of a hanging barrel. underneath the hanging barrel. a secondary support is placed in the bottom of the vessel. There is a long riser above the core outlet to enhance the natural circulation capability. There are four primary heat exchangers in the downcomer between the riser and the vessel wall. The reactor core is cooled by natural circulation and the carried heat is transferred to the intermediate circuit vir primary heat exchangers.



❶core ❷primary heat exchanger

❸RPV ❹containment

Fig.1 The NHR-5 structure with dual vessel

Dual pressure vessel

The dual pressure vessel is adopted in the design of NHR-5. The reactor pressure vessel is designed for an operation pressure of 1.5MPa. Outside the RPV, a second metalic vessel-containment(quard vessel) is mounted. The design pressure is 1.5MPa at the temprature of 177°C. The gap between the RPV and containment is very small. All RPV penetrations are located higher than core outlet atleast 3m, and there are no large -bore pipes.

All of these measures can void and mitigate serious consequences which result from the loss of coolant accident. If the RPV had been broken at its bottom the core can also be covered with water. The Fig. 1 shows the reactor structure with dual vessel.The main parameters of dual pressure vessel is listed in Table 3.

Table 3 The main parameters of dual pressure vessel

Pressure vessel		
ID	m	1.8
Total height	m	6.5
Working pressure	MPa	1.5
Working temprature	°C	198
Material		22g
Lining thichness (Braze welding)	mm	~ 6
Thichness of cylinder	mm	90
Total weight	t	35
Containment(quard vessel)		
ID	m	2.8
Total height	m	9.5
Thichness of wall	mm	20
Design temperature	°C	177
Design pressure	MPa	1.5
Material		16MnR
Weight	t	29

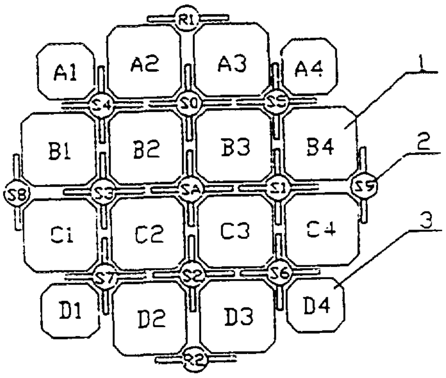
Self-pressurized system

A space above the coolant level inside the RPV is as a self - pressurized space (~ $1 m^3$). The pressure inside the RPV is depends on initial partial pressure of nitrogen and saturate vapour pressure corresponds to the core outlet temperature in the pressurized water operation mode. Due to the nitrogen partial pressure existing, the coolant can be kept subcooling in the core outlet. This is called pressurized water operation mode.

2.2 Overall Arrangement of Reactor Core

Reactor core

The core cross section of NHR-5 is shown in Fig.2. In the core there are 12 fuel assemblies with 96 fuel rods and 4 with 35 fuel rods. The fuel rod with cladding of Zircaloy-4 has an active length of 690mm and a diameter of 10mm. The nuclear fuel is uranium dioxide with an enrichment of 3%. The total amount of UO_2 loaded in the core is 0.508 tons.



❶ Assembly with 96 fuel rods ❷ Control rod
❸ Assembly with 35 fuel

Fig.2 The cross section of NHR-5

Control of reactivity

The reactivity is controlled by a combination of fuel rods containing fixed burnable poison of 1.5% Gd_2O_3, movable absorption rods(boron carbide) and negative reactivity efficient. In the core there are 13 control rods which are all driven by a new hydraulic driving system. The control rod driving system consists of three parts: an actuating loop outside the containment, 13 hydraulic step cylinders in the core and two control units (combine valves). The control rods can be dropped into the core by gravity when the reactor shutdown is needed. Boron injection system as a standby shutdown system is initiated by pumps or pressurized nitrogen during event of ATWS.

2.3 Main Heat Transfer System

The main heat transfer system is composed of three circuits, i.e. the primary circuit, the intermediate circuit and heat grid. The intermediate circuit is singl loop which connects with the primary circuit and heat grid via the four primary heat exchangers and 2 intermediate heat exchangers. 4 primary heat exchangers are divided into two groups in parallel operation, which are merged single loop through isolating valves. The operating pressure in the intermediate circuit is higher than the primary circuit which can keep the heat grid free of radioactivity. Heat generated in the core is transferred to the heat grid via the intermediate circuit. The main heat transfer system is shown as Fig.3.

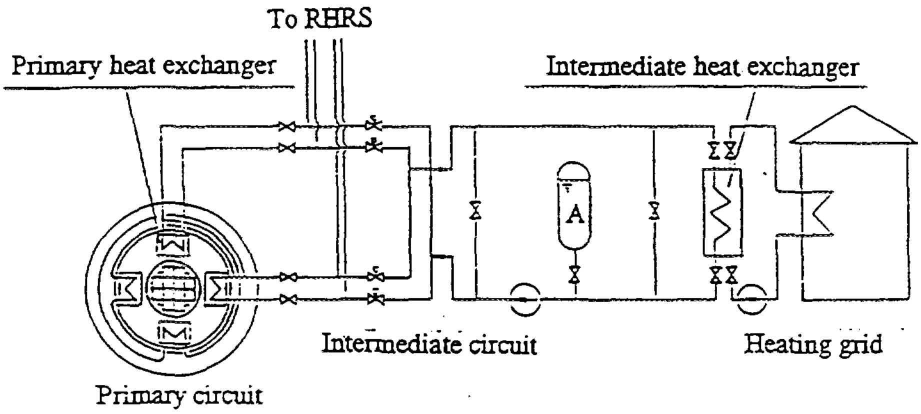


Fig. 3 Main heat transfer system of NHR-5

2.4 Residual Heat Removal System

The residual heat removal system (RHRS) of the NHR-5 consists of two independent trains which assigned to two groups of primary heat exchangers. There are three natural circulation cycle for each train. Figure 4 shows the schematic system diagram of the RHRS. After reactor shut-down the decay heat will be transferred to the intermediate circuit via the primary heat exchangers. Then the heat carried is going to a vaporizer located at a high position in the reactor hall. This is the first natural circulation cycle. The second one consists of the vaporizer.air cooler and related pipes and valves. Finaly, the decay heat can be discharged to the atmosphere via the air cooler located on the roof of the building by natural convection of air.

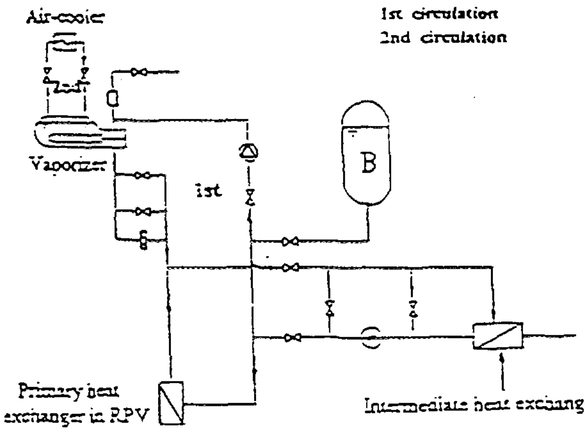


Fig.4 Schematic system diagram of RHRS

3. Operatinal Experience of NHR-5

3.1 Reactor operation condition

Start up

Star up of the NHR-5 is a process from cold condition to the expecting operation state by means of nuclear heating itself. During the start up process three things have to be made i.e. to set up initial partial pressure of nitrogen in RPV.to limit the rising temperature rate less 50°C/hr in primary circuit and to keep the coolant level at a certain range in RPV. Fig. 5 shows the start up process with the fullexternal load.

Feeding nitrogen and water into RPV

Nitrogen and water into the RPV to compensate their loss caused by various reasons(mainly sampling) are made up from time to time for keeping the normal operation condition of NHR-5.

As a result of feeding gas into RPV, the reactor power increases with increase in pressure and comes to a peak, after that it begins to decrease and finally reaches a new steady state. The result is given in Fig. 6. In the process of this experiment, the reactor power increased 5.7%, the core inlet and outlet temperature rised 1.1°C and 1.4°C respectively. The variation of reactor power indicates there is a certain void content in the core at operation condition.The reactor has similar behavior when the water feeds into the RPV.Water fed into the RPV via purification system is reheated by a regenerative heat exchangers. and enters to the downcomer and then into the core. Due to the coolant level rising and fed water temperauture being less than the coolant temperatuthe the core inlet temperature has slight decrease and the pressure increases. For the both reasons of pressure rising and temperature decreasing the reactor power increase. The experimental results are given in Fig. 7.

Self-pressurized performance

A space in the upper part of the vessel is used for the self-pressurized space. Total pressure in RPV is formed by both nitrogen partil pressure of 0.3MPa and saturate steam partial pressure of 1. 17MPa which correspond to the core outlet temperature of 186°C .

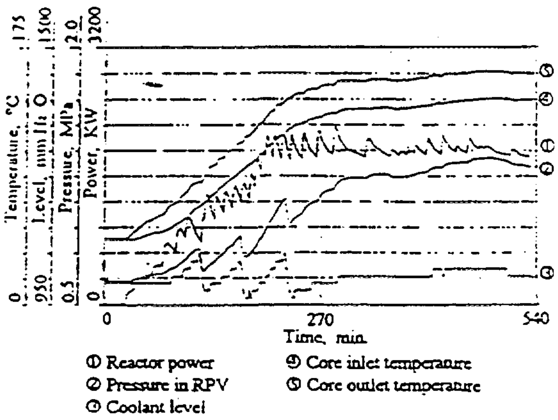


Fig. 5 The start up process of NHR

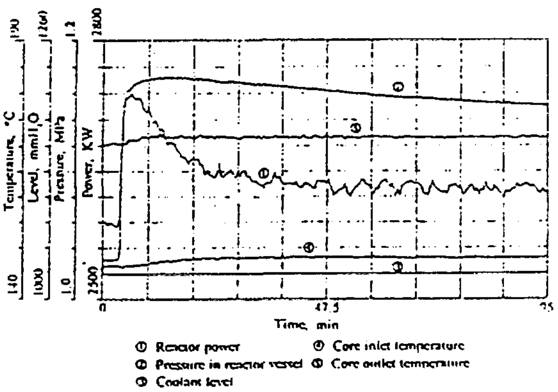


Fig.6 feeding nitrogen into the RPV

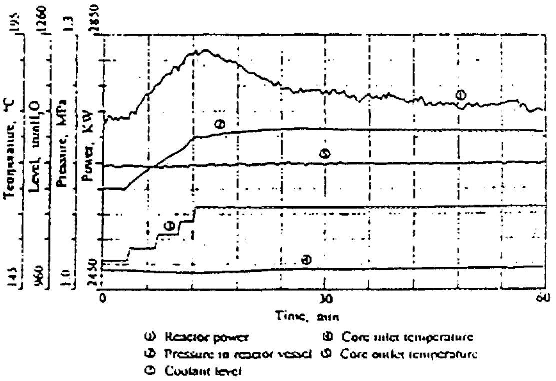


Fig. 7 Feeding coolant water into the RPV

The change of the total pressure in RPV caused by various transient conditions are smooth and small, which result from the large coolant inventory and large self-pressurized space. For example, when the external load changed in 60% the total pressure in RPV only changed in 5%. The change in total pressure is by reasons of both changes of core outlet temperature and coolant level.

High operation availability

As a heating reactor, the NHR-5 is only operated in winters. The operation availability of the NHR-5 is evaluated by comparing the actual operated days with the planned operation days. From December 1989 to March 1993, the NHR-5 has been operated for more than 9330 hours. The average avaibility of heating operation was about 99%. There were four times of unexpected reactor shutdwon caused mainly by failure of electric power supply and auxiliary systems during the four winters operation. Each duration of reactor shutdown was less than 4 hours, so space heating was not affected very much due to the great heat capacity of the heat grid. In spite of the fact that the NHR-5 is the first vessel type heating reactor, it has reached a high availability of heating operation.

3.2 Radiation Protection and Environmental Impacts

Specific radioactivity of water in three loops

During operation the water radioacivity level in the primary circuit, intermediate circuit and heating grid have been regularly monitored. The radioactive back-ground of potable water in this area is about 0. 10 Bq/l. The radioacivity level in the water of the intermediate circuit and the heating grid are as low as that of the potable water. In the primary circuit the specific radioactivity of coolant is at the level of 2.5×10^2-2.7×10^3Bq/l. The nuclide analysis showed there were no fission products in the coolant. From the point of view of radioactivity isolating the intermediate circuit performs a perfect function to keep the heating grid free of radioactivity.

r-exposure rate

The distribution of *r* - exposure rate in the NHR -5 building is reasonable. A large part of the building have very low *r*-exposure rate near the background level. A higher *r*-exposure rate is found outside the biological shielding where the regenerative heat exchanger of the primary purification system is placed here. A local shielding with lead has to be added to reduce the *r*-exposure rate.

Effluent

During normal operation . the gaseous effluent radioactivity level is at the same level as that of the background. The nuclides analysis indicated that there was no artificial nuclide in the effluent. the nuclides in the effluent are natural ^{40}K and Radon daughters.The amount of waste water, produced from operation and maitenance is about 10.2m^3 in four years.

Collective dose

The collective dose for all operators in each heating period are also very low, and are indicated in Table 4.

Table 4 Collective dose for all operators in each heating period

Period	Collective dose (mSv-man)
1989.11-1990.3	2.4
1990.11-1991.2	3.2
1991 11-1992.3	11.4

In addition, there are many items regularly monitored on the onsite and offsite, such as γ -exposure rate, gross β - radioactivity level of aerosal and liquid effluent, the sample of water, soil, air, plants and so on.

All measuring data indicate the NHR-5 operation do not cause any change in radioactivity level in this area.

3.3 Water chemistry of NHR-5

In consideration of the features of NHR-5: low temperature, low power density, and refueling interval being longer than PWR, and by reference to the operation experience of nuclear powered ship " Otto Hahn" a water chemistry system different from the PWR and BWR is adopted in the operation of NHR-5. This water chemistry system is in neutrol water, not to contain boron and not to add hydrogen in premary coolant, and oxygen removed by chemical additive (C_2H_4).

The results of monitoring and analysis show the dissolved oxygen can maitain the level of 40 ppb and pH value of 6-7. Table 5 listed the analysis results and the specification of primary coolant.

Table 5 Specification and monitored results for primary coolant

iterm	specification	analysis results
dissolved oxygen	<50ppb	30-40 ppb
pH(25°C)	6-10	6-7
F	< 100ppb	< 50ppb
Cl	< 100ppb	< 50ppb
Cr	< 10ppb	< 0.1ppb
Fe	< 10ppb	< 0.05ppb
Na	< 5 ppb	< 5ppb
Cu	—	< 0.2ppb
NO_3^-	—	< 5ppb
NO_2^-	—	< 5ppb
total solid	< 1ppm	< 0.5-1ppm

The nitrate and nitrite are less than 5 ppb in the coolant at any operation conditions. This concentrate is too low to cause metal structure to corrode. So nitrogen used as covered gas is feasible for NHR-5.

In order to effectively decrease the dissolved oxygen level in the primary coolant, the followings will be considered in the future operatio: to remove the oxygen from the makeup water, to add additive into the primary circuit continously and to exhaust the air from the nitrogen supply lines, especialy during replacement of the nitrogen cylinder.

3.4 Operation of Intermediate Circuit

To maitain isolating fuction

The pressure in the intermediate circuit is higher than that in primary circuit in order to keep isolating function. The RHRS is a part of intermediate circuit during reactor in normal operation. In this case the pressure in the intermediate circuit depends on the pressure of pressurized tank (A) in this circuit. When the intermediate circuit is isolated the isolating condition depends on the pressure of the pressurized tanks (B and C) installed in the RHRS. The two pressurized tanks are connceted to the RHRS by small bore valves and pipes. The advantage is that the isolating function can be kept after large loss of water in the intermediate circuit.

Detection of leakage rate for the intermediate circuit

The changes in water level in three pressurized tanks (A、B and C) is used for detecting the leakage rate. This method is applicable for the steady operation state. The operation practice indicates the normal leakage rate is about 1 l/hr.

3.5 Operation of RHRS

The reactor residual heat is removed by a passive residual heat removal system which connects to the intermediate circuit. There are two independent trains of the RHRS which composed of three natural circulation loops. (See Fig. 4)

Hot standby condition

When the reactor is operated in normal condition, the RHRS is working at the hot standby condtion. In this case the vaporizer of RHRS and primary heat exchangers work in parallel and a very small flow of the intermediate loop passes through the vaporizer to prevent freezing in the air-cooler. In order to set up the second circulation-vaporization and condensation, the air in the shell side of vaporizer has to be discharged at its high temperaure.

Direction of natural circulation

When the RHRS is put in operation the primary heat exchanger and vaporizer will work from parallel mode to series mode. So the direction of water flow must change in the vaporizer or the primary heat exchangers, which is dependent on the temperature distribution in this system. In gerneral, if reactor is operated at high power level the direction of natural circulation will be the same as in primary heat exchanger, if reactor at low power level, the direction will be the same as in vaporizer. The experimental results indicated two circulative direction has same capacity to remove the decay heat from the core.

From the experimental results it is indicated that the natural circulation of the RHRS can be reliably established and the direction of natural convection in the intermediate circuit did not effect the decay heat removal.

Capability test of RHRS

According to the principle of thermal energy balance the heat removal capability of RHRS is measured at a steady operation state of NHR-5. The heat generated in reactor core should be balanced by the heat loss, the heat cooled by purifaction system and the heat removed by the RHRS. A heat removal capability of 116KW was measured at the average temperature of 166°C in the primary circuit. This value is more than the design value of 75 KW for each train.

In addition the RHRS can be operated at a temperature lower than 100°C, and has a certain capability to remove the residual heat from the core. It shows the reactor can be cooled down to the cold shutdown condition by the RHRS only.

3.6 Operational status of control rod driving system

The control rod driving system was satisfactory for starting up, regulating reactor power and reactor shutdown during the past operation. The full travel time for dropping into the core is less than 2 seconds.

Owning to use of the temperature compensation device in the hydraulic driving system, to adjust the flow rate at high temperature is not neccesseary indeed.

The ultrasonic position indicator were also satisfactory for indicating the position of control rod under the pressurized water operation mode. The ultrasonic indicator system can not work under two phase flow or the condition with a interface of gas and liquid. Therefore, the correct position of control rod would not be indicated in this system as the loss of pressure or fast pressure reduction inside RPV.

4. Safety Features Experiment of NHR-5

In the course of commissioning and operation, a number of experiments have been carried out to demostrate the feasibility and safety of the vessel type heating reactor concept. In these experiments there are no any external interference of the operators.

4.1 Self-regulation Feacture

The self-regulation experiment has been performed to investigate the reactor self-regulation ability to follow the change of heating load. The heating load can be varied by means of changing the flow rate through the intermediate heat exchangers.

The flow rate through the intermediate heat exchangers was from 8 t/hr to 35 t/hr, then back to 8 t/hr. This value corresponds to a heating load change from 1.5 MW to 2.5 MW, a variation of about 66%. Figure 8 shows the behaviour of NHR-5 following the heating load change. The reactor power caused by the self-regulating mechanism automatically to vary after 90 seconds, reached a new power level to match the heating load within 30 minutes. The moderator temperature coefficient plays a main role in this process. The experimental results show that the NHR-5 has a very good self regulation ability to follow a load change without any operator action.

4.2 Self-stability Feature

The self-stability experiment was performed in order to investigate the response of reactivity insertion. In this experiment the reactor was operated at a power of 2.5 MW, then a step insertion of 2 mk reactivity was introduced. Figure 9 indicates the variation of reactor parameters. At the beginning of the transient the reactor power increased rapidly due to the extra reactivity and reached a maximum relative value of 1.18 in 100 seconds.Then the reactor power began to decrease due to the feedback of negative reactivity coefficient and came to a new relative power level of 1.08 in 30 minutes. The core inlet and outlet temperatures added an increment of 3.8°C and 4.2 °C correspondingly. The reactor pressure increased with a Δp of 0.102 MPa.

4.3 Experiment for ATWS

In order to study the safety behaviour of the NHR-5, in 1990 an experiment has been carried out.

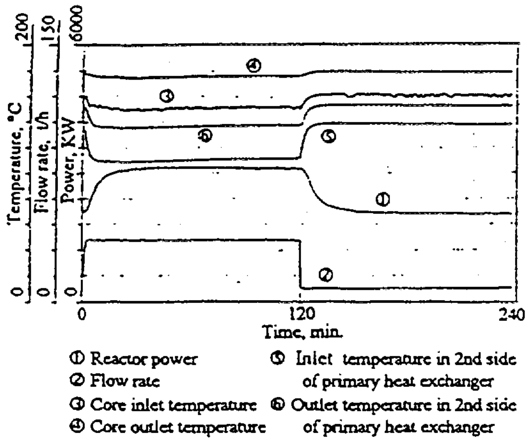


Fig.8 The feature of self-regulation at NHR-5

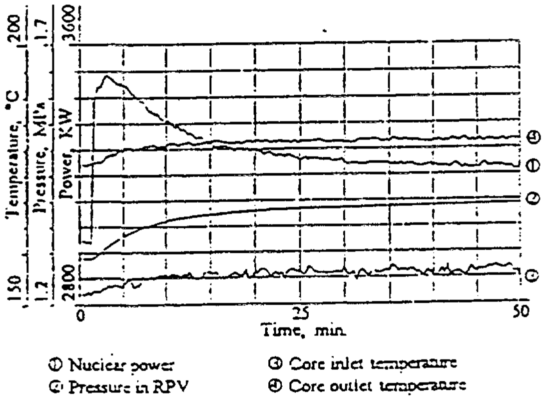


Fig. 9 The feature of self-stability at NHR-5
(Inserting reactivity of $2\times10^{-3}\Delta k/k$)

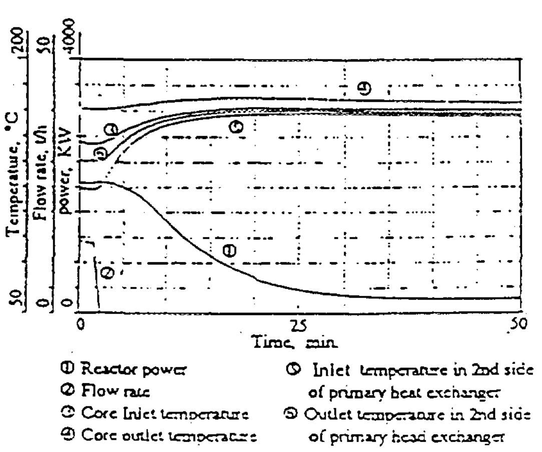


Fig.10 The transient of loss heat main heat sink without scram

which simulated the ATWS, i.e. a loss of the main heat sink followed by the failure of all 13 shutdown control rods.

In this experiment, the intermediate heat exchangers was isolated at a reactor power of 2 MW, and noneof the shutdown . rods was inserted. Figure 10shows the power variation observed together with the changes in temperaure and pressure of the reactor. The power decreased as a consequence of feedback of the negative temperature coefficient to a stable value of about 0.2 MW in about 30 minutes. The inlet and outlet temperature of the reactor core rised by 20.4°C and 4.7° C respectively. The temperature variation is not serious at all. The primary system pressure rised by 0.23 MPa. The result of the experiment demonstate that the NHR-5 has excellent inherent and passive safety features. The ractor will be shutdown passively even in the described ATWS case.

4.4 Residual heat removal under the interruption of natural circulation in the primary circuit
When a loss of coolant accident (LOCA) occurs in the primary circuit, the water level inside the RPV will decrease. Due to the integrated arrangement of the primary circuit and all penetration of small pipes located at the upper part of the vessel the reactor core will never be uncovered. But as a result of the water level decrease the natural circulation of the primary circuit might be interrupted. In this case the residual heat of the reactor will be transported by vapor condensed at the uncovered tubes of the primary heat exchangers.

To demonstrate the capability of residual heat removal under LOCA conditions a special experiment was carried out at the NHR-5 in March 1992. After reator shut down the water in the reactor vessel was discharged by opening the valve to the blowdown tank. The water discharge rate was 1.6m³/hr and an amount of 2.4m³ water was drained off. The water level in the reactor vessel decreased below the entrance of the primary heat exchanger and the natural circulation was interrupted. In this case the residual heat removal was mainly realized by condensation of the vapor. Due to the discharge of 2.4m³ water the partia pressure of nitrogen reduced from 0. 29 MPa to 0.022MPa. so that the water subcooling of the reactor outlet temperature decreased from 12 °C to 2 °C.

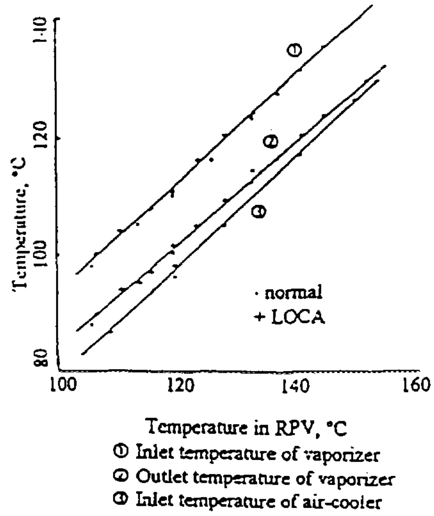


Fig. 11 The comparison of normol and abnormal operation codition ofNHR-5

The reduction of sub-cooling enhansed the vaporization - condensation process. Figure 11 shows the comparison of the residual heat removal capabilities during LOCA conditions and under the normal operation. From the results of the comparision it can be shown that the procedures of both LOCA and normal operation are almost the same. The decay heat can be reliably removed by means of vapor condensation on the primary heat exchanger under LOCA conditions.

5. Summary

During four winters of NHR-5 heating operation. the reactor has been known as a valuable tool for a number of experiments on operation behaviors and safety features. The operational and experimental results have successfully demonstrated the inherent and passive safety characteristics of NHR-5. It was proven that the design concept and technical measures of NHR are suitable to meet the requirements for distric heating in northern cities, congeneration and air condition in the middle cities of China, as well as the seawater desalination.

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